Inferring Zonal Irregularity Drift from Single-Station Measurements of Amplitude (S_4) and Phase (σ_ϕ) Scintillations

Charles S. Carrano, Susan H. Delay,
Keith M. Groves, Patricia H. Doherty
Institute for Scientific Research, Boston College

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Introduction

- To model GNSS scintillation one must characterize the field-aligned ionospheric irregularities that scatter the satellite signals.

- In addition to their spectral properties (power spectral strength, spectral index, anisotropy ratio, and outer-scale), the horizontal drift of the irregularities must be specified.

- The irregularity drift is important from a system impacts perspective because it controls the rate of signal fluctuations (all other factors being equal). This influences a GNSS receiver's ability to maintain lock on the signals.

- At low latitudes the irregularity drift is predominantly zonal and is controlled by the F region dynamo and regional electrodynamics. It is traditionally measured by cross-correlating observations of satellite signals made using a pair of closely-spaced receivers.

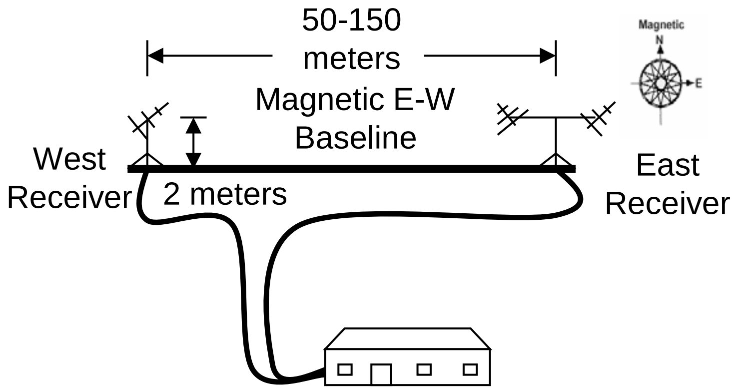
- The AFRL-SCINDA network operates a small number of VHF spaced-receiver systems at low latitude stations for this purpose.

- A far greater number of GNSS scintillation monitors are operated by AFRL-SCINDA (25-30) and the Low Latitude Ionospheric Sensor Network/LISN (35-50), but the receivers are situated too far apart to monitor the drift using cross-correlation techniques.

Introduction

- Most methods for estimating the zonal irregularity drift are variations of the spaced-antenna technique [Vacchione et al., *Radio Sci*., 1987; Spatz et al., *Radio Sci*., 1988]. When only a stand-alone receiver is available, the spaced-receiver technique cannot be applied.

- Nevertheless, previous attempts have been made to measure the irregularity drift using a stand-alone receiver by correlating observations of slant TEC between different satellites [Liang et al., 2009; Ji et al., 2011]. Unfortunately, the different scan directions of the satellites with respect to the irregularities generally results in a low correlation.



- Here we describe an alternative approach that leverages the weak scatter theory [Rino, *Radio Sci*., 1979] to infer the zonal irregularity drift from single-station measurements of S_4, σ_φ, and the propagation geometry.

- We have applied the technique to a month of data (November, 2013) from three SCINDA stations where both GPS and VHF spaced-receiver data are available.

Geographic coordinates and magnetic dip angles for the three stations considered:

Station	Lat.	Lon.	Dip Angle
Bangkok (BKK)	14.1°N	100.6°E	14.0°N
Cape Verde (CVD)	16.73°N	22.9°W	18.5°N
Kwajalein (KWA)	9.4°N	167.5°E	8.5°N

The Basic Concept

- According to the theory, both S_4 and σ_φ depend on the irregularity strength and propagation geometry, but only σ_φ depends on the irregularity drift through the effective scan velocity.

- Our technique leverages this to infer the effective scan velocity from measurements of the ratio σ_φ / S_4. Once the effective scan velocity is known, the zonal irregularity drift can be calculated.

Amplitude scintillation

$$S_4^2 = C_p \rho_F^{p-1} F_S(p) \wp(p)$$

Phase scintillation

$$\sigma_\varphi^2 = C_p F_\sigma(p) G \left[V_{eff} \tau_c \right]^{p-1}$$

Table of Symbols

C_p – phase spectral strength due to irregularities
ρ_F – Fresnel scale = $[z \sec \theta / k]^{1/2}$
p – phase spectral index
k – signal wavenumber
θ – propagation (nadir) angle
z – vertical propagation distance past screen
$\wp(p)$ – combined geometry and propagation factor
G – phase geometry enhancement factor
$F_s(p)$, $F_\sigma(p)$ – functions of p only
V_{eff} – effective scan velocity
τ_c – time constant of the phase detrend filter

Measuring the Zonal Irregularity Drift

Divide σ_φ by S_4 so that irregularity strength (C_p) cancels, then solve for V_{eff}:

$$V_{eff} = \frac{\rho_F}{\tau_c}\left[\frac{F_S(p)}{F_\sigma(p)}\frac{\wp(p)}{G}\frac{\sigma_\varphi^2}{S_4^2}\right]^{1/(p-1)}$$

Table of Symbols

ψ – magnetic inclination angle

φ – magnetic azimuth of propagation

θ – propagation (nadir) angle

V_{px}, V_{py}, V_{pz} – mag. components of IPP vel.

A,B,C – coefficients of transformation from propagation dir. to principal axes

V_D – zonal irregularity drift

From the weak scatter theory:

Effective scan velocity

$$V_{eff}^2 = \frac{CV_{sx}^2 - BV_{sx}V_{sy} + AV_{sy}^2}{AC - B^2/4}$$

Scan velocity (assuming drift is purely zonal)

$$V_{sx} = -[V_{px} - \tan(\theta)\cos(\varphi)V_{pz}]$$

$$V_{sy} = V_D - [V_{py} - \tan(\theta)\sin(\varphi)V_{pz}]$$

Combining the above and solving for the zonal irregularity drift gives

$$V_D = (V_{py} - \tan(\theta)\sin(\varphi)V_{pz}) - \frac{B}{2A}(V_{px} - \tan(\theta)\cos(\varphi)V_{pz})$$
$$\pm\frac{1}{A}\sqrt{[AC - B^2/4][AV_{eff}^2 - (V_{px} - \tan(\theta)\cos(\varphi)V_{pz})^2]}$$

Infinite Axial Ratio Model

- The weak scatter theory accommodates anisotropic irregularities with elongation along two principal axes. At low latitudes, irregularities are rod-like and we can derive a simpler result:

Taking the formal limit as the axial ratio becomes infinitely large gives

$$V_{eff} = \frac{\rho_F}{\tau_c} Q_\sigma(p) \left[\frac{\sigma_\varphi}{S_4} \right]^{\frac{2}{p-1}} \qquad Q_\sigma(p) = \left[\frac{2^{(p+1)/2} \pi^{p-1/2} \Gamma\left[(5-p)/4\right]}{\Gamma\left[(1+p)/4\right]} \right]^{1/(p-1)}$$

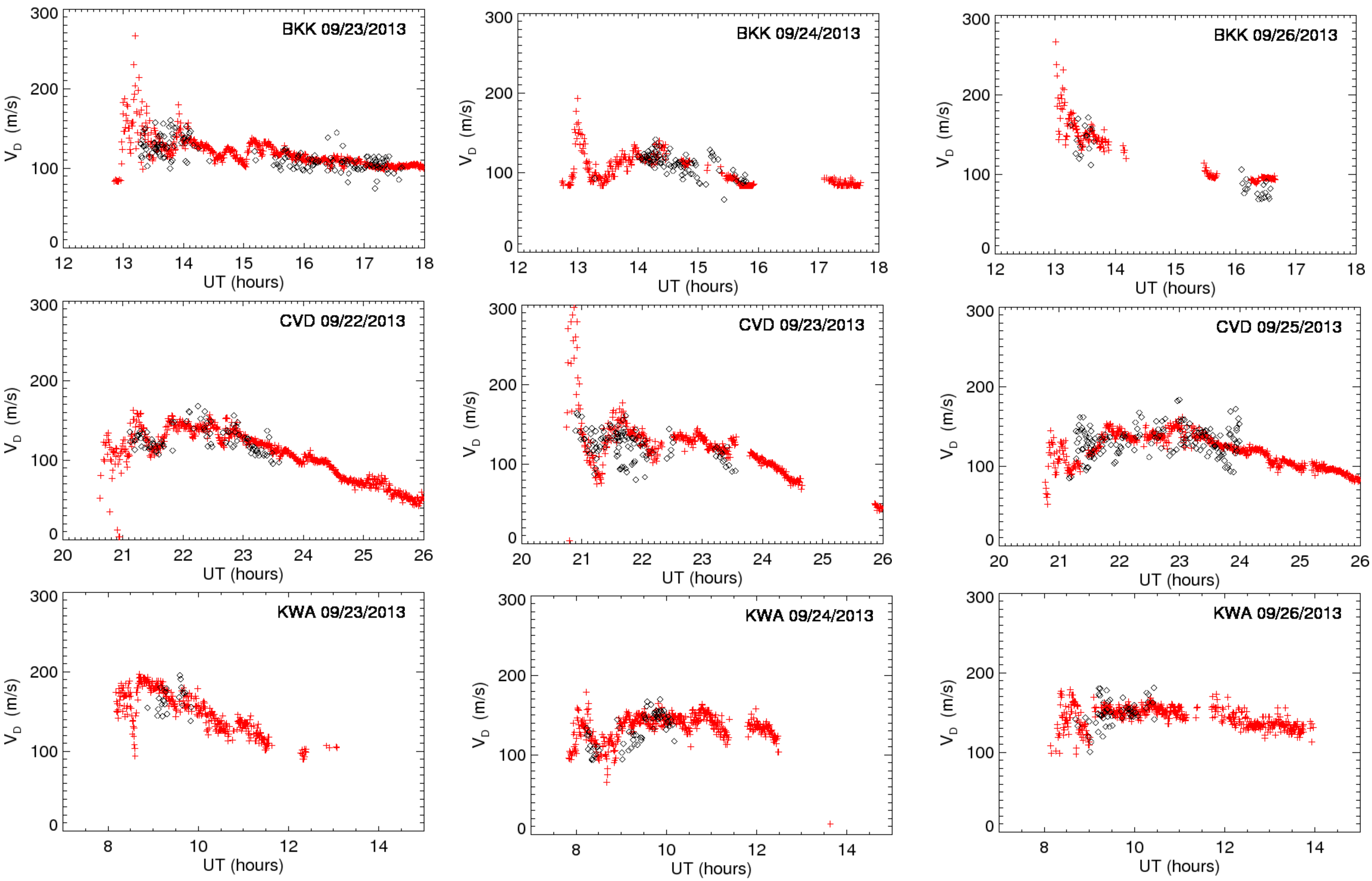
and the zonal irregularity drift becomes:

$$V_D \approx V_{py} + \frac{(V_{px}\sin\psi - V_{pz}\cos\psi)\sin\varphi\tan\theta}{\cos\psi - \cos\varphi\sin\psi\tan\theta} \pm \sqrt{1 + \frac{\sin^2\varphi\tan^2\theta}{(\cos\psi - \cos\varphi\sin\psi\tan\theta)^2}}\, V_{eff}$$

This simpler model gives zonal drift estimates within ~ 5 m/s of the finite axial ratio model with a:b = 50:1 (used by WBMOD)

Example Results

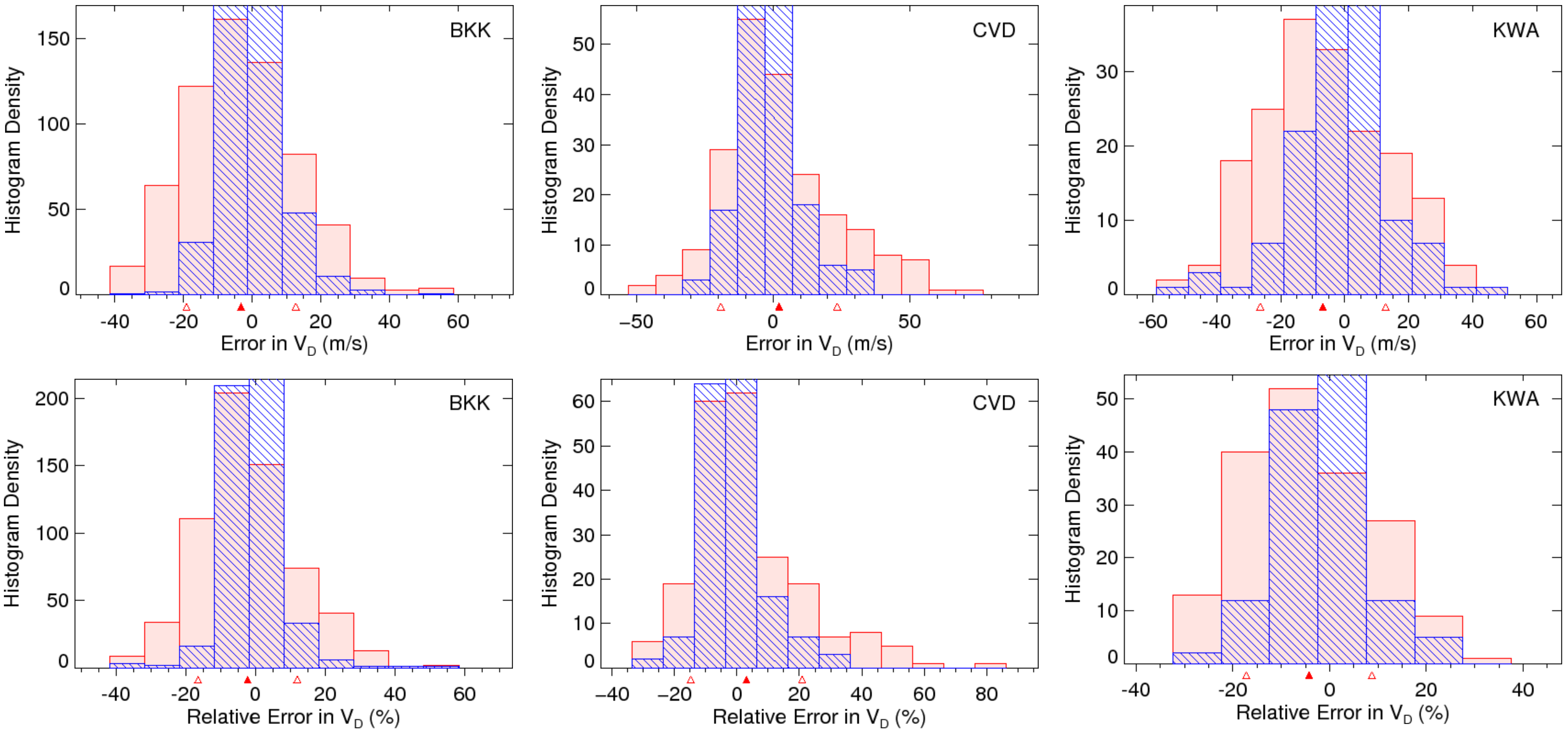
Zonal drift for 3 evenings at Bangkok (top), Cape Verde (middle), and Kwajalein (bottom) measured with a stand-alone GSV4004B scintillation monitor (black diamonds) and VHF spaced-receivers (red crosses)



Statistical Validation

- We compared stand-alone GPS and VHF spaced-receiver estimates of the zonal drift at the three stations for all days with scintillation in November 2013 (selected for convenience).

- These histograms show the difference (in m/s) between each sample and the median drift calculated from the VHF data using 5 minute bins.



Red = GPS drift; Blue = VHF spaced-receiver drift

Interpretation

- To assist with interpretation, we introduce constraints that are *not* required to estimate the drift.

- In the case of vertical propagation the infinite axial ratio model implies

$$V_D \approx V_{py} \pm \frac{\rho_F}{\tau_c} Q_\sigma(p) \left[\frac{\sigma_\varphi}{S_4} \right]^{2/(p-1)}$$

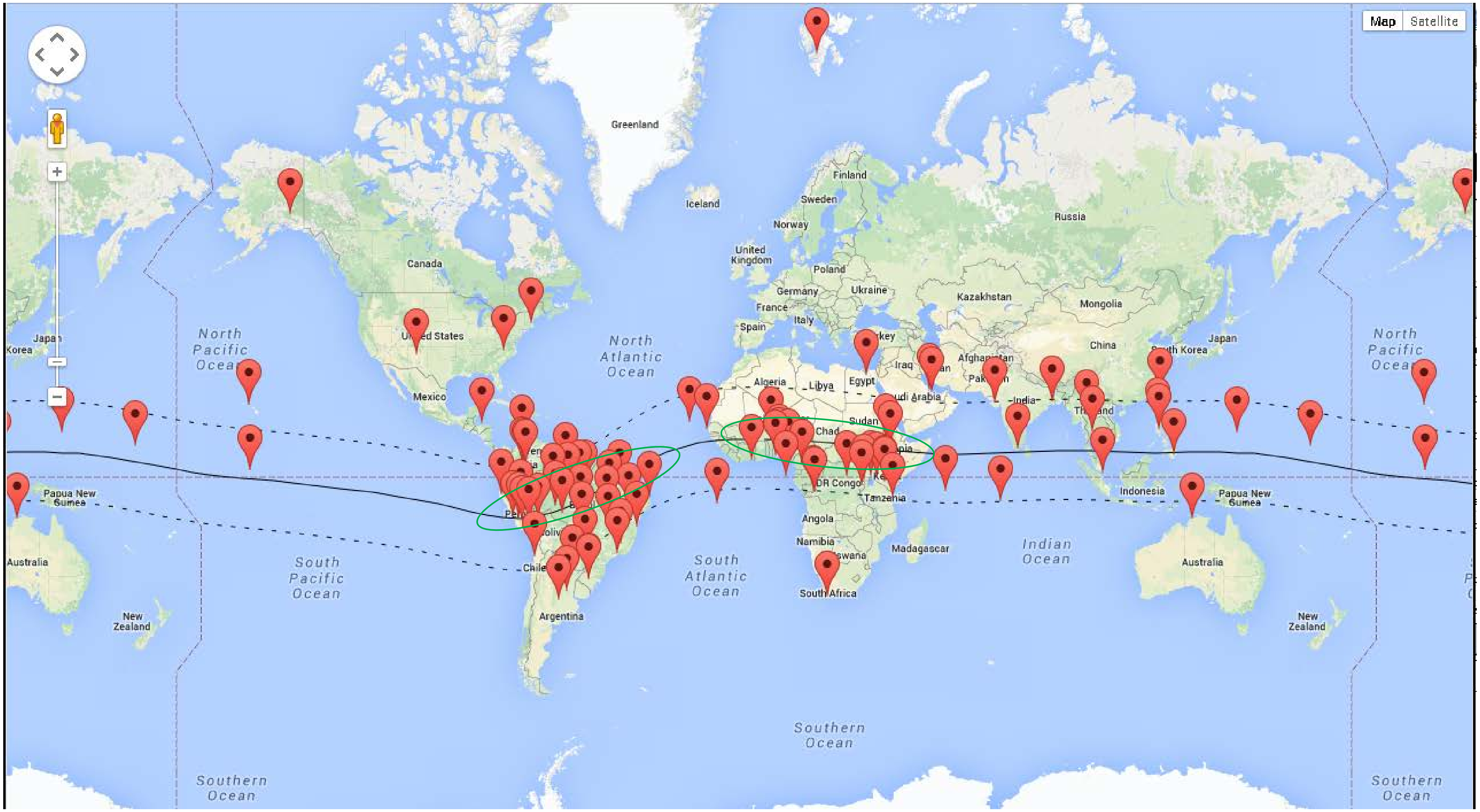
- If we also assume p=3 (typical) and τ_c = 10 sec (default for most scintillation monitors) then

$$\frac{\sigma_\varphi}{S_4} \approx \frac{V_D - V_{py}}{1.11\rho_F}$$

- S_4 depends on the distance to the irregularities through the Fresnel parameter.
- σ_φ is proportional to the difference between the zonal drift and IPP motion toward magnetic east.
- The ionospheric perturbation strength affects both S_4 and σ_φ but *not their ratio*. If this ratio is measured and the distance to irregularities is known, we can infer the zonal drift.

Future Directions

The SCINDA and LISN networks include a large number of GNSS scintillation monitors suitable for estimating the zonal drift. With continent-scale zonally distributed chains of receivers one could continuously monitor the zonal drift and explore its longitudinal morphology. Two suitable receiver chains in South America and Africa appear circled in green.



Summary

- We developed a technique that leverages the weak scatter theory to infer the zonal drift from single-station GNSS measurements of S_4, σ_φ, and the propagation geometry.

- By judicious selection of the scattering layer height and spectral index, we are able to obtain estimates of the zonal irregularity drift that are unbiased and with a spread about the mean of 15-20 m/s (10-15%).

- The simplified version of the model, which assumes infinitely elongated rod-like irregularities, provides drift measurements within 4 m/s (8 m/s) for satellites above 45° (30°) elevation compared with the more complex finite axial ratio model.

- While this technique is not intended to supplant direct measurement of the zonal irregularity drift made by spaced-receivers, it should prove useful for the *vast majority* of GNSS scintillation monitors that are too distant from their neighbors to apply the spaced-receiver technique.

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For more information on this work, contact charles.carrano@bc.edu